

Design features to achieve defence-in-depth in small and medium sized reactors

Vladimir Kuznetsov

International Atomic Energy Agency

Abstract. Broader incorporation of inherent and passive safety design features has become a ‘trademark’ of many advanced reactor concepts, including several evolutionary designs and nearly all innovative small and medium sized design concepts. Ensuring adequate defence-in-depth is important for reactors of smaller output because many of them are being designed to allow more proximity to the user, specifically, when non-electrical energy products are targeted. Based on the activities recently performed by the International Atomic Energy Agency, the paper provides a summary description of the design features used to achieve defence in depth in the innovative concepts of small and medium sized reactors with fast neutron spectrum.

1. Introduction

According to the categorization adopted by the International Atomic Energy Agency (IAEA), small and medium sized reactors (SMRs) are those with the equivalent electric output less than 700 MW. In many cases, deployment potential of SMRs is supported by their ability to fill niches in which they would address market situations different from those of currently operated large-capacity nuclear power plants — the situations that value more distributed electrical supplies or a better match between capacity increments and investment capability, or more flexible siting and greater product variety. Ensuring adequate defence-in-depth is important for reactors of smaller output because many of them are being designed to allow more proximity to the user, specifically, when non-electrical energy products are targeted.

Upon the advice and with the support of IAEA member states, the IAEA provides a forum for the exchange of information by experts and policy makers from industrialized and developing countries on the technical, economic, environmental, and social aspects of SMR development and implementation in the 21st century, and makes this information available to all interested Member States by producing status reports and other publications dedicated to advances in SMR design and technology development [1,2].

In 2009 IAEA has published a Nuclear Energy Series report titled “Design Features to Achieve Defence in Depth in Small and Medium Sized Reactors” [3]. The objective of this report is to assist developers of SMRs in member states in defining consistent defence in depth approaches regarding the elimination of accident initiators/ prevention of accident consequences by design and the incorporation of inherent and passive safety features and passive systems into safety design concepts of such reactors.

The SMRs addressed in [3] represent different reactor lines, intended for different applications, and targeting different deployment timeframes. The reactor lines considered are pressurized water reactors — the KLT-40S (35 MW(e), OKBM, Russian Federation), the IRIS (335 MW(e), Westinghouse, USA), the CAREM-25 (27 MW(e), CNEA, Argentina), the SCOR (630 MW(e), CEA, France), and the MARS (150 MW(e), University of Rome “La Sapienza”, Italy), targeted for co-generation or electricity production; pressurized boiling light water cooled heavy water moderated reactors — the AHWR (BARC, India), targeted for electricity generation with potable water production; high temperature gas cooled reactors — the GT-MHR (287.5 MW(e), General Atomics, USA), targeted for

electricity generation and advanced non-electrical applications, including complex cogeneration with bottoming cycles; sodium cooled and lead cooled fast reactors — the 4S-LMR (50 MW(e), CRIEPI, Toshiba, Japan) and the SSTAR and the STAR-LM (19.7 and 181 MW(e), both – ANL, USA), targeted for electricity production or cogeneration; and non conventional very high temperature designs — the CHTR (100 kW(e), BARC, India), targeted for hydrogen production and other advanced non-electrical applications. Of those, the addressed fast reactor concepts (4S-LMR, the SSTAR and the STAR-LM), and the non-conventional design (CHTR) are factory fabricated reactors capable of more than a decade of operation without on-site refuelling [2].

The descriptions in reference [3] were structured to follow the definitions and recommendations of the IAEA safety standard NS-R-1 “Safety of the Nuclear Power Plants: Design Requirements” [4], which provides for the following five levels of defence in depth:

- Level 1 – Prevention of abnormal operation and failure;
- Level 2 - Control of abnormal operation and detection of failure;
- Level 3 - Control of accidents within design basis;
- Level 4 - Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe accidents; and
- Level 5 - Mitigation of radiological consequences of significant release of radioactive materials.

This paper will present general findings of the new IAEA report [3] and provide more details about the innovative fast-spectrum small reactors without on-site refuelling.

2. Summary of design approaches

2.1. General approach and considerations

An enveloping design approach for all SMR designs addressed is to eliminate as many accident initiators and/or to prevent as many accident consequences as possible, by design, and then to deal with the remaining accidents/consequences using plausible combinations of the active and passive safety systems and consequence prevention measures. This approach is also targeted for Generation IV energy systems and, to a certain extent it is implemented in some near-term light water reactor designs of larger capacity, such as the VVER-1000, the AP1000, and the ESBWR [4].

General features of SMRs that, in view of their designers, contribute to a particular effectiveness of the implementation of inherent and passive safety design features in smaller reactors are:

- Larger surface-to-volume ratio, which facilitates easier decay heat removal, especially with a single-phase coolant;
- An option to achieve compact primary coolant system design, e.g. integral pool type primary coolant system, which could contribute to an effective suppression of certain initiating events;
- Reduced core power density, facilitating easy use of many passive features and systems;
- Lower potential hazard that generically results from lower source term owing to lower fuel inventory, lower non-nuclear energy stored in the reactor, and lower integral decay heat rate.

2.2. Approaches and considerations for sodium cooled and lead cooled fast reactors

All of the considered fast-spectrum SMRs offer design flexibility in setting desired combinations of reactivity coefficients and effects. This flexibility, coupled with the inherent properties of the advanced types of fuel, creates a potential to prevent transient overpower accidents; to ensure increased reactor self-control in a variety of other anticipated transients without scram and

combinations thereof; and to enable “passive shutdown”¹ and passive load following capabilities for a plant². Smaller specific core power or relatively tall reactor vessels facilitate the use of natural convection of a single-phase liquid metal coolant to remove decay heat or even the heat produced in normal operation (for heavy liquid metal cooled SMRs). For sodium cooled reactors, smaller reactor size facilitates achieving negative whole-core sodium void reactivity effect. For lead cooled reactors, there could be a certain size limit to ensure a reliable seismic design [1].

Figure 1 and 2 show general layouts of the 4S-LMR and the SSTAR, respectively.

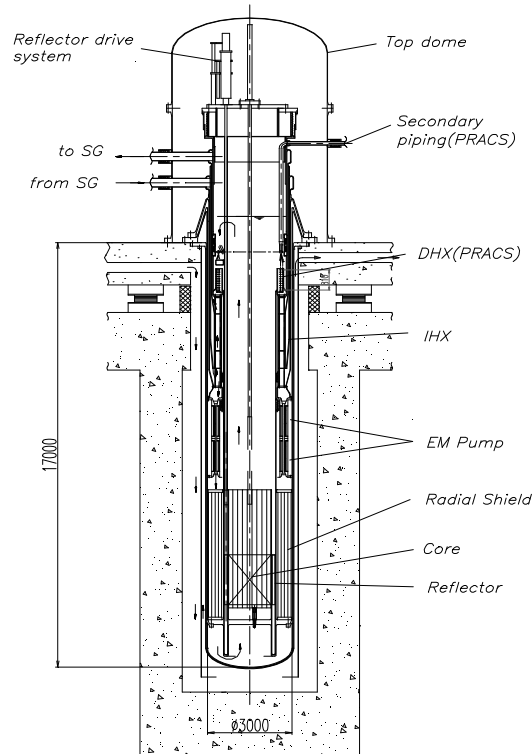


FIG. 1. Vertical view of the 4S-LMR layout.

Fast-spectrum liquid metal cooled SMR designs are represented by the 4S-LMR concept of a sodium cooled small reactor without on-site refuelling developed by the Central Research Institute of Electric Power Industry (CRIEPI) and Toshiba in Japan and by the SSTAR and STAR-LM concepts of small lead cooled reactors without on-site refuelling developed by the Argonne National Laboratory (ANL) in the USA. The lead cooled SMR concepts use CO₂ as working media in the Brayton cycle power circuit, and incorporate no intermediate heat transport system. Although essentially different in several important features, both sodium cooled and lead cooled SMR concepts belong to a family of pool-type integral design liquid metal cooled fast reactors, and close cooperation between their designers has been established long ago [3]. Of the two designs, the 4S-LMR is in a more advanced stage, because for a similar design, different essentially in the type of fuel and named the 4S, the basic design and

¹ “Passive shutdown” is used to denote bringing the reactor to a safe low-power state with balanced heat production and passive heat removal, with no failure to the barriers preventing radioactivity release to the environment; all relying on the inherent and passive safety features only, with no operator intervention, no active safety systems being involved, and no external power and water supplies being necessary; and with practically infinite grace period.

² It should be noted that such features of liquid metal cooled reactors as passive load following and “passive shutdown” have been more analyzed in the past for smaller-sized reactors, such as EBR-II of 65 MW(th) or PRISM of 850 MW(th). However, for sodium and lead cooled fast reactors, there are no reasons that such features couldn’t be realized in larger reactors with nitride or metallic fuel. Certain analytical studies carried out in the past provide preliminary proofs of this [5].

major parts of the system design have been completed [3] A pre-application review by the US NRC has been initiated in the fall of 2007, and a formal licensing application is scheduled for 2010. Different from it, both the SSTAR and STAR-LM are at a pre-conceptual stage. It should be noted that small size and capacity of the fast reactors considered in [3] are, first-of-all, conditioned by the requirement of operation without on-site refuelling [2] and not by the a priori considerations of achieving a somewhat higher degree of passive response in accidents.

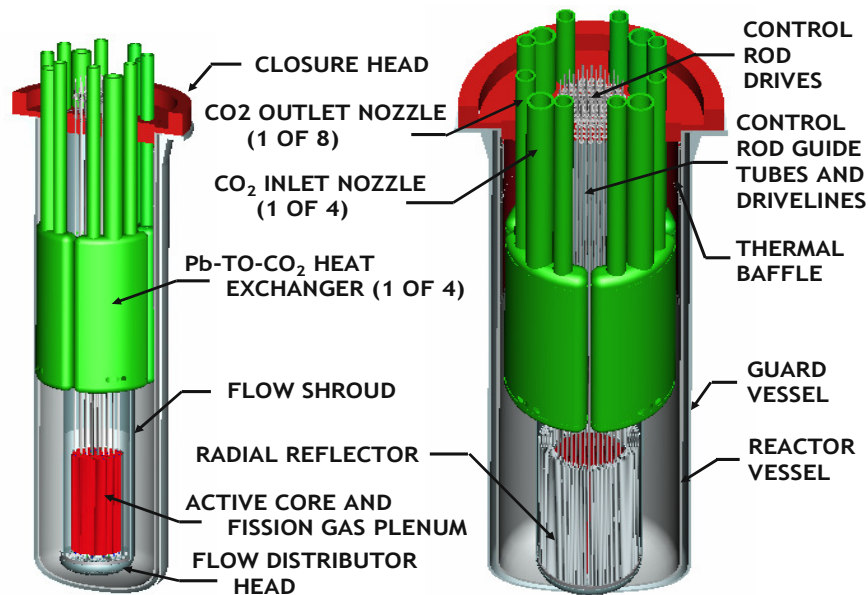


FIG. 2. General view of the SSTAR layout.

Design features of the 4S-LMR and the SSTAR and the STAR-LM contributing to Level 1 of defence in depth, “Prevention of abnormal operation and failure”, are summarized in Table 1.

TABLE 1. DESIGN FEATURES OF SODIUM COOLED AND LEAD COOLED FAST SMRS CONTRIBUTING TO LEVEL 1 OF DEFENCE IN DEPTH

#	DESIGN FEATURE	WHAT IS TARGETED	SMR DESIGNS
1	Low-pressure primary coolant system	Low non-nuclear energy stored in the primary coolant system – elimination of a potential of release of this energy	4S-LMR, SSTAR, STAR-LM
2	Use of metallic fuel with high thermal conductivity (relatively low temperature)	High margin to fuel failure	4S-LMR
3	Use of nitride fuel with high thermal conductivity (relatively low temperature)	High margin to fuel failure	SSTAR, STAR-LM
4	Relatively low linear heat rate of fuel	Higher margin to fuel failure	4S-LMR
5	Power control via pump flow rate in the power circuit, with no control rods in the core	Elimination of an accident with control rod ejection	4S-LMR
6	Large negative feedbacks from fast-spectrum core plus natural convection of the coolant in all modes, enabling passive load following and “passive shutdown”	Essential prevention or de-rating of the initiating events resulting from malfunctioning of the systems or components, or operator actions that would otherwise need to be considered as sources of failure	SSTAR, STAR-LM

#	DESIGN FEATURE	WHAT IS TARGETED	SMR DESIGNS
7	Low burn-up reactivity swing over long core lifetime/ refuelling interval	Elimination of transient overpower accident due to control rod ejection	SSTAR, STAR-LM
8	Elimination of feedback control of moveable reflectors (that compensate for reactivity changes due to fuel burn-up); a pre-programmed reflector drive system is used	Prevention of transient overpower	4S-LMR
9	Electromagnetic impulsive force used in the reflector driving system	Intrinsic limitation of the speed of positive reactivity insertion	4S-LMR
10	Intermediate heat transport system	Prevention of sodium-water reaction	4S-LMR
11	Pb coolant not reacting chemically with CO ₂ working fluid; no intermediate heat transport system	Elimination of a chemical interaction between the primary coolant and the working fluid of a power circuit	SSTAR, STAR-LM
12	Natural convection of the coolant plus open fuel element lattice (large fuel element pitch-to-diameter ratio)	- Elimination of loss of flow accidents; - Prevention of flow blockage accidents	SSTAR, STAR-LM
13	Primary electromagnetic (EM) pumps arranged in two units connected in series, with each unit capable of taking on one half of the pump head	Prevention of loss of flow	4S-LMR
14	The reactor vessel enclosed in a guard vessel to prevent loss of the primary coolant; pool type design with intermediate heat exchangers located inside the main reactor vessel	Prevention of loss of coolant (LOCA)	4S-LMR
15	Use of double piping, double tubes and double vessels for the secondary sodium, including heat transfer tubes of the steam generator	- Prevention of LOCA - Prevention of sodium-water reaction	4S-LMR
16	- The reactor vessel enclosed in a guard vessel such that even in the case of primary vessel boundary rupture, the faulted level of lead will always exceed the Pb entrances to the PB-to-CO ₂ heat exchangers; - High boiling point of the Pb coolant (1740°C), exceeding the point at which stainless steel core structures melt; - Pool type design configuration; - High density of Pb coolant limits void growth and downward penetration following a postulated in-vessel heat exchanger tube rupture.	Prevention of loss of coolant (LOCA) and its possible consequences	SSTAR, STAR-LM
17	High-reliability system of control of dissolved oxygen potential in the Pb coolant	- Maintaining the integrity of stainless steel cladding in all modes of operation by preventing corrosion ³ ; - Prevention of the formation of corrosion debris with a potential to block coolant area.	SSTAR, STAR-LM

³ Corrosion/erosion is generally a slow and easily detectable process.

Low-pressure primary coolant system, securing low non-nuclear energy stored in the primary coolant system is a common feature of all liquid metal cooled reactors, irrespective of their size and capacity. In addition to it, like many innovative liquid metal cooled reactors of a variety of capacities and sizes, all SMRs considered in this section rely on advanced fuel designs with high thermal conductivity, ensuring increased margins to fuel failure.

The lead cooled SSTAR and STAR-LM reactors incorporate optimum sets of reactivity feedbacks, provided by design and contributing to the elimination of transient overpower, as well as to the prevention or de-rating of the initiating events resulting from malfunctioning of systems or operator actions. Specifically, the designers of the SSTAR and STAR-LM mention the so-called “passive shutdown” capability of their reactors as provided by design.

The sodium cooled 4S-LMR provides for power control via pump flow rate in the power circuit, with no control rods in the core, and for pre-programmable movement of axial reflectors with no feedback control, contributing to burn-up reactivity compensation. Both of these features contribute to the prevention of transient overpower accidents.

To prevent sodium-water reaction, the 4S-LMR incorporates intermediate heat transport system, like most of the sodium cooled fast reactors. As the CO₂ is used as a working medium in the power circuits of the SSTAR and STAR-LM, which does not react chemically with Pb, these reactors do not incorporate intermediate transport system.

Natural convection is used in the SSTAR and STAR-LM to remove heat under normal operation, eliminating loss of flow accidents. De-rating of loss of flow in the 4S-LMR is achieved by a scheme with two electromagnetic pumps connected in series.

Both sodium and lead cooled SMRs incorporate guard vessel to prevent LOCA; the 4S-LMR also incorporates double piping and double vessels for secondary sodium, including heat transfer tubes of the steam generator.

Finally, reliable system of corrosion control is assumed to be provided for the SSTAR and STAR-LM to maintain the integrity of stainless steel claddings and to prevent the formation of the corrosion debris with a potential of coolant area blockage. For these reactors it is important to maintain the oxygen potential in the correct regime to prevent the formation of PbO, which needs to be avoided. There could also be corrosion debris such as Fe that migrates into the coolant where it forms iron oxide that should be filtered out.

Design features of the 4S-LMR and the SSTAR and the STAR-LM contributing to Level 2 of defence in depth, “Prevention of abnormal operation and failure”, are summarized in Table 2.

TABLE 2. DESIGN FEATURES OF SODIUM COOLED AND LEAD COOLED FAST SMRS CONTRIBUTING TO LEVEL 2 OF DEFENCE IN DEPTH

#	DESIGN FEATURE	WHAT IS TARGETED	SMR DESIGNS
1	All-negative temperature reactivity coefficients	Increased self-control of abnormal operation	4S-LMR
2	Large negative feedbacks in fast spectrum core; natural convection of the coolant in all modes; physical properties of Pb coolant and nitride fuel with high heat conductivity	Increased self-control of abnormal operation, including passive load following and “passive shutdown”	SSTAR, STAR-LM
3	Large thermal inertia of the coolant and the shielding structure	Slow pace of the transients due to abnormal operation	4S-LMR, SSTAR, STAR-LM
4	Sodium leak detection system in the heat transfer tubes of the steam generator, capable of detecting both inner and outer tube failures	Enhanced detection of failure of the secondary sodium boundary	4S-LMR
5	Two redundant power monitoring systems; balance of plant temperature	Enhanced control of abnormal operation and detection of	4S-LMR

#	DESIGN FEATURE	WHAT IS TARGETED	SMR DESIGNS
	monitoring system; electromagnetic pump performance monitoring system; cover gas radioactivity monitoring system, etc.	failure	
6	System of monitoring of the dissolved oxygen potential in the Pb coolant	Control of the corrosion/erosion processes of stainless steel claddings in Pb flow and detection of failures	SSTAR, STAR-LM
7	Independent and redundant shutdown systems (see Table 30 for details)	Reactor shutdown	All designs

For Level 2 of defence in depth, “Control of abnormal operation and prevention of failure”, the contributions come from large thermal inertia of the primary coolant system and reactor internals, resulting in a slow progress of transients, and from optimum negative feedbacks, provided by design and ensuring high-degree of reactor self-control. Specifically, passive load following and “passive shutdown” capability are mentioned for the SSTAR and STAR-LM. Monitoring and detection systems are other important contributors. Finally, independent and redundant active or passive shutdown systems are available for the cases when all other measures of control and prevention turn out to be ineffective.

Design features of the 4S-LMR and the SSTAR and the STAR-LM contributing to Level 3 of defence in depth, “Prevention of abnormal operation and failure”, are summarized in Table 3.

TABLE 3. DESIGN FEATURES OF SODIUM COOLED AND LEAD COOLED FAST SMRS CONTRIBUTING TO LEVEL 3 OF DEFENCE IN DEPTH

#	DESIGN FEATURE	WHAT IS TARGETED	SMR DESIGNS
1	Use of metallic fuel with high thermal conductivity (relatively low temperature)	High margin to fuel failure; larger grace period	4S-LMR
2	Use of nitride fuel with high thermal conductivity (relatively low temperature)	High margin to fuel failure; larger grace period	SSTAR, STAR-LM
3	Relatively low linear heat rate of fuel	Higher margin to fuel failure; larger grace period	4S-LMR
4	All-negative temperature reactivity coefficients	Increased reactor self-control in design basis accidents	4S-LMR
5	Large negative feedbacks from fast spectrum core, natural convection of the coolant in all modes, physical properties of Pb coolant and nitride fuel with high heat conductivity	Increased self-control of the reactor in design basis accidents, including passive load following and “passive shutdown” (in the case of a failure of both scram systems)	SSTAR, STAR-LM
6	Negative whole-core void worth	Prevention of design basis accidents propagation into beyond design basis conditions (due to coolant boiling or loss)	4S-LMR
7	<ul style="list-style-type: none"> - Very high boiling point of Pb coolant (1740 °C); - Escape path for gas/void to reach free surface provided by design; - The reactor vessel is enclosed in a guard vessel such that even in the case of primary vessel boundary 	Prevention of core void as the extension of design basis accidents; securing of normal heat removal path through Pb/CO ₂ heat exchangers in DBA	SSTAR, STAR-LM

#	DESIGN FEATURE	WHAT IS TARGETED	SMR DESIGNS
	rupture, the faulted level of lead will always exceed the Pb entrances to the PB-to-CO ₂ heat exchangers.		
8	Large specific (per unit of power) inventory of the primary coolant	Increased grace period	4S-LMR, SSTAR, STAR-LM
9	Effective radial expansion of the core (negative feedback), provided by design	Increased reactor self-control in design basis accidents; prevention of DBA propagation into beyond design basis conditions	4S-LMR, SSTAR, STAR-LM
10	Low pressure loss in the core region, provided by design	Increased level of natural circulation to remove decay heat from the core	4S-LMR
11	A combined system of electromagnetic pumps and synchronous motors (SM), ensuring favourable flow coast-down characteristics	Increased grace period in the case of pump failure	4S-LMR
12	Natural convection of the coolant in all modes of operation plus open fuel element lattice (large fuel element pitch-to-diameter ratio)	Increased reliability of heat removal by natural convection of the coolant via Pb-CO ₂ heat exchangers and, in the case of their failure, by natural convection based decay heat removal systems RVACS and DRACS	SSTAR, STAR-LM
13	Two independent systems of reactor shutdown, each capable of shutting down the reactor by: - A drop of several sectors of the reflector; or - Gravity-driven insertion of the ultimate shutdown rod.	Reactor shutdown	4S-LMR
14	Two independent and redundant active safety grade shutdown systems	Reactor shutdown ⁴	SSTAR, STAR-LM
15	Redundant and diverse passive auxiliary cooling systems (RVACS and IRACS or PRACS), both using draught of environmental air as an ultimate heat sink	Increased reliability of decay heat removal from the core	4S-LMR
16	Two or more safety grade independent Direct Reactor Auxiliary Cooling System (DRACS) providing independent paths for decay heat removal. The reactor vessel auxiliary cooling system (RVACS), if present, will be a single safety grade decay heat removal system. If RVACS and DRACS are both present, this provides even a greater diversity. However, if DRACS are effective, the role of RVACS would be reduced. All systems will use natural draught	Increased reliability of decay heat removal from the core (especially, when the normal path via Pb-CO ₂ heat exchangers becomes unavailable)	SSTAR, STAR-LM

⁴ It is noted that the operation of these systems may actually be unnecessary because the inherent and passive features are in any case capable to ensure a “passive shutdown”.

#	DESIGN FEATURE	WHAT IS TARGETED	SMR DESIGNS
	of air as an ultimate heat sink.		
17	Use of double piping, double tubes and double vessels for the secondary sodium, including heat transfer tubes of the steam generator	Prevention of steam generator tube rupture, sodium-water reaction, and pressure increase in the intermediate heat transport system	4S-LMR
18	Passive pressure relief from primary coolant system	Protection of the reactor vessel and enclosure from over-pressurization in the case when one or more of the in-vessel Pb-to-CO ₂ heat exchanger tubes fail	SSTAR, STAR-LM

For Level 3 of defence in depth, “Control of accidents within design basis”, the contribution comes for the following main groups of design features:

- (1) Inherent safety features, highlighted in positions 1–8 of Table 3. In addition to the features already discussed in conjunction with defence in depth levels 1 and 2, it is important to note negative whole-core void worth provided by design in the 4S-LMR and inherent features of the lead cooled SSTAR and STAR-LM, practically eliminating the option of coolant boiling or gas bubbles arriving to the core (preventing the propagation of a design basis accident into a severe accident with transient overpower);
- (2) By-design provisions for certain passive mechanisms such as radial expansion or enhanced level of natural convection in the primary coolant system, highlighted in positions 9–12 of Table 3;
- (3) Two independent systems of reactor shutdown, provided in each design; see positions 13–14 of Table 3. Those operate based on gravity in the 4S-LMR, while in the SSTAR and the STAR-LM both systems are active and safety grade. For the SSTAR and STAR-LM, it is mentioned that the operation of these systems may actually be unnecessary because the inherent and passive features are in any case capable to ensure a “passive shutdown” of the reactor;
- (4) Not less than two redundant and diverse passive decay heat removal systems in each design, with some of them, possibly, providing several passive decay heat removal paths, and all using natural draught of air as an ultimate heat sink, positions 15–16 of Table 3;
- (5) Special design features provided to prevent or mitigate the effects of pressurized medium from the power circuit getting into the primary circuit; positions 17–18 of Table 3.

The 4S-LMR incorporates no active safety systems. However, there are several active systems providing normal operation of the reactor at rated or de-rated power, e.g., electromagnetic pumps providing forced convection of sodium coolant to remove core heat, or burn-up reactivity compensation system based on slow upward movement of the reflector, using advanced pre-programmed drive mechanism. These systems can contribute to performing safety functions in certain accident scenarios. No information was provided on which systems of the 4S-LMR are safety grade.

All passive and active safety systems in the SSTAR and the STAR-LM are assumed to be safety grade.

The design feature contributing to Level 4 of defence in depth, “Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe accidents” fit in the following main groups; see Table 4:

- (1) The inherent safety features contributing to prevention of core melting;
- (2) Redundant and diverse passive decay heat removal systems with natural draught of air used as an ultimate heat sink, discussed in more detail in conjunction with Level 3 of defence in depth;
- (3) Inherent and passive design features for the prevention of recriticality. Those include an effective mechanism of fuel carry-over from the core in the case of fuel element cladding failure (4S-LMR) and

high density of the Pb coolant securing that molten fuel is moved to the upper free level of lead (SSTAR and STAR-LM);

(4) Guard vessels in addition to the main vessels, for all designs, and double piping for the 4S-LMR;

(5) The containment and reactor location in a concrete silo below the ground level, for all designs considered.

For Level 5 of defence in depth, “Mitigation of radiological consequences of significant release of radioactive materials”, the designers of the 4S-LMR foresee no measures needed beyond the plant boundary in response to any severe accidents and combinations thereof, even in the case when there is no operator intervention, no emergency team actions, and no external power and water supply. The designers of the SSTAR and STAR-LM take a more conservative approach, suggesting that standard measures may still be applicable but within the exclusion zone reduced against that of the present day reactors.

2.3. Reduced off-site emergency planning

The designers of most of the SMRs addressed in reference [3] foresee that safety design features contributing to defence in depth levels 1–4 could be sufficient to meet the objective of the defence in depth level 5 “Mitigation of radiological consequences of significant release of radioactive materials”, i.e., that the emergency planning measures outside the plant boundary might be reduced or even not needed at all. The design features of the SMRs indicated to make a contribution directly to Level 5 of defence in depth are lower fuel inventory, lower non-nuclear energy stored in the reactor, and lower integral decay heat rate of a smaller reactor as compared to the large-capacity one

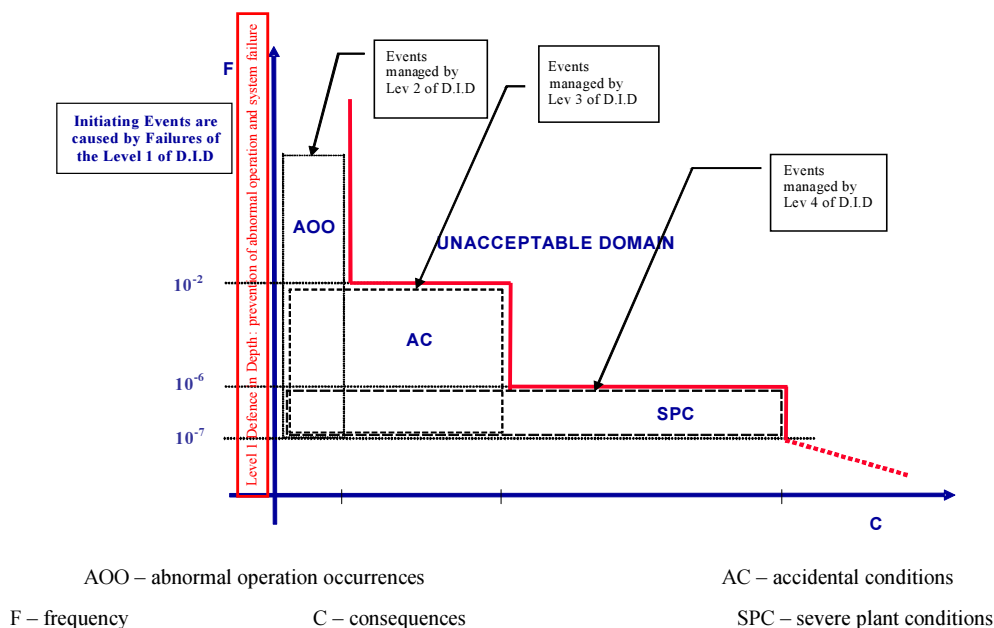


FIG. 3. Quantitative safety goal and correlation of levels of defence in depth [8].

As a desired or possible feature, reduced off-site emergency planning is mentioned in the Technology Goals of the Generation IV International Forum, in the user requirements of the IAEA’s International Project on Innovative Reactors and Nuclear Fuel Cycles (INPRO) [6], and in the recommendations of the International Nuclear Safety Advisory Group (INSAG-12) [7], with a caution that full elimination of off-site emergency planning may be difficult to achieve or with a recommendation that Level 5 of defence in depth still needs to be kept, notwithstanding its possibly decreased role. Achieving the goal of a reduced off-site emergency planning would require both, development of a methodology to prove that such reduction is possible in the specific case of a plant design, and adjustment of the existing regulations.

Risk-informed approach to reactor qualification and licensing could facilitate licensing with reduced off-site emergency planning for smaller reactors, once it gets established⁵. Within the deterministic safety approach it might be very difficult to justify reduced emergency planning in view of a prescribed consideration of a postulated severe accident with radioactivity release to the environment owing to a common cause failure. Probabilistic safety assessment (PSA), as a supplement to the deterministic approach, might help justify very low core damage frequency (CDF) or large early release frequency (LERF), but it does not address the consequences and, therefore, does not provide for assessment of the source terms.

Risk-informed approach that introduces quantitative safety goals, based on the probability-consequences curve could help solve the dilemma by providing for a quantitative measure for the consequences of severe accidents and by applying a rational technical and non-prescriptive basis to define a severe accident. An example of such approach is provided in the IAEA-TECDOC-1570 [8], see Fig. 3. As of today, such an approach is not yet established as an IAEA safety standard.

3. Conclusion.

For all SMRs design concepts addressed in reference [3], the designers expect that prototype or first-of-a-kind plants with their respective SMRs would be licensed according to the currently emplaced regulatory norms and practices in member states. Further advancement of regulatory norms toward risk-informed approach could then facilitate design improvements in the next plants and, specifically, help justify reduced off-site emergency planning. Further revisions of the IAEA safety standards toward a technology-neutral approach⁶ could be of value to facilitate design development and safety qualification of non water cooled SMRs, including small fast reactors, such as the 4S-LMR, the SSTAR and STAR-LM.

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⁵ Risk-informed regulations for beyond design basis accidents are already emplaced in some member states, e.g., Argentina.

⁶ National regulations in some member states are already technology-neutral; the examples are the United Kingdom or the Russian Federation